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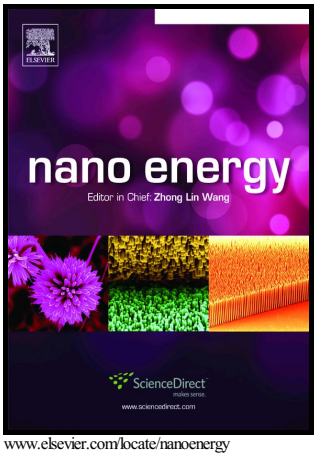

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Transparent triboelectric generators based on glass and polydimethylsiloxane

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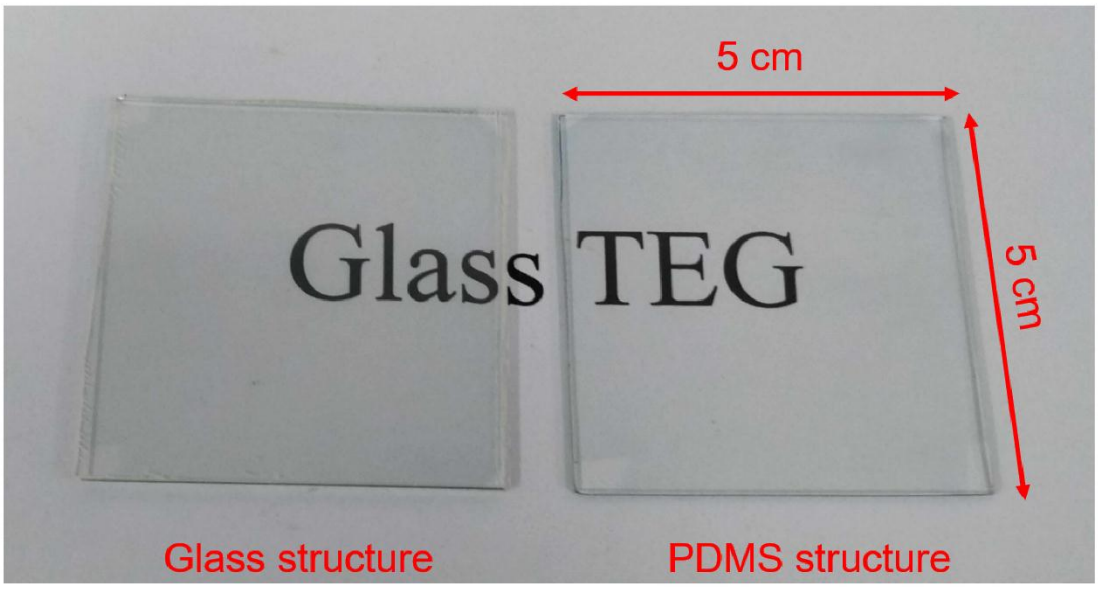
Abstract

Glasses are widely used in modern society, mostly for achieving brightness for buildings, transportations etc. Here a transparent triboelectric generator (TEG) based on commercially available glasses and PDMS plates is proposed and fabricated to harvest mechanical energy. Using flat glass and PDMS plates, an open voltage up to 850 V, 20.6 μA short circuit current and 3.13 mW power are achieved for devices with 5 cm × 5 cm dimension, whereas the transparency of glass and PDMS structures exceeds 81% and 89%, respectively. The TEGs show excellent mechanical stability and reliability upon cyclical contact for 10,000 times. The voltage and power outputs of the glass based TEGs improve with increasing contact force, frequency and distance, and with decreasing glass thickness and humidity level. Our results demonstrate the feasibility to utilize abundant glass windows to fabricate transparent TEGs for energy harvesting, which could make a great contribution to the sustainable development.

Graphical abstract



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Glass TEG shows good transparency, electric performance and the feasibility to turn the abundant glass windows into energy harvesting applications.

Keywords: transparent, glass based, triboelectric generator

1. Introduction

Renewable energy and their technologies are highly sorted nowadays for sustainable development and preservation of good environment, not just for our generation, but also for next generations. Many renewable energy technologies such as solar cells,[1-3] solar thermal systems,[4, 5] biofuels[6, 7] and tidy- or wave-based generators[8, 9] etc, have been developed in large scales, to partially replace fossil fuel based energy resources and reduce the catastrophic impact to environment and greenhouse effect. For small scale, energy harvesting technologies such as microgenerators based on piezoelectric[10-12] and pyroelectric[13, 14] effects etc have been intensively studied and exploited for applications. Microgenerators utilizing the electrostatic and electrification effects,[15, 16] the so-called triboelectric generators (TEG), to produce electricity is one of the latest technologies. TEGs can convert waste mechanical energies such as vibration, impact, shock and natural forces such as wind and rains into electricity.[17-19] So far, TEGs are mostly used to power sensors and microsystems. However, the output voltages and powers of TEGs could be up to several thousands of volts and 30 mW/cm^2,[20, 21] much higher than those by other microgenerator technologies, therefore it can be renewable energy, not only for sensor networks and microsystems, but also possibly for high power applications if potential resources can be utilized. Furthermore, TEGs have much higher energy conversion efficiency, up to 80%[22], compared to other microgenerators, much simpler device structures and fabrication processes, and can be made at much lower cost with no request for cutting-edge technology and clean room manufacturing environment.

Glass has been intensively used in modern society, in skyscrapers, houses, transportations etc, it could become a vast energy resource if it can be utilized for energy generation or harvesting. Transparent solar cell has been proposed to convert Sun light into electricity[23], however the necessity to absorb light by solar cells for electricity generation directly conflicts the original purpose of glasses used in buildings etc, therefore, transparent solar cells will

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have limited success and application. Glasses have high positive electronic affinity in triboelectric series, and thus are particularly suitable for the fabrication of TEGs, but so far no glass based TEGs work has been reported.

Here we propose to develop transparent TEGs using commercially available glasses and polydimethylsiloxane **(**PDMS**)** as the triboelectric materials. The simple TEGs show an open-voltage, short-circuit current and power up to 850 V, 20.6 μA and 3.13mW, respectively, for a device area of 5 cm × 5 cm. The integrated devices have the transparency 73.6% in visible light region, thus would not affect the brightness of buildings at all, demonstrating its great potential for application. With further development of this technology, it is anticipated that the abundant glasses in modern society could be turned into massive devices and systems to harvest waste mechanical energies such as wind, vibration, impact etc, which could make a significant contribution to the forthcoming era of sustainable development.

2. Fabrication and experimental setup

There are mainly three modes of TEGs, namely the vertical contact-separation mode, lateral sliding mode and single electrode mode.[24] We use the vertical contact-separation mode for our transparent TEGs demonstration. Figure 1(a) is the three dimensional (3D) schematic structure of the TEG device. It consists of a glass part and a PDMS part with a fixed dimension of 5 cm × 5 cm for both of them. Commercially available soda lime glasses (the main compositions are sodium carbonate, lime, dolomite, silicon dioxide, aluminum oxide etc, while the detail compositions are subjected to commercial secret) with five different thicknesses (0.18 mm purchased from Asahi Glass, 0.55 mm, 1 mm, 2 mm and 3 mm purchased from China Luoyang Float Glass Group Co. Ltd.) were used as the substrates for the fabrication of TEGs, to demonstrate its practical potential and applications. To achieve the transparency, an indium tin oxide (ITO) transparent conductive layer (750 nm, $R_{\square}$=4.7 Ω/□) was deposited by direct-current reactive magnetron sputtering on the glass substrates as the electrode. The optimized sputtering conditions of the power, pressure and bias voltage were 150 W, 0.7 Pa and -75 V, respectively.[25] The glass samples were then annealed to obtain better electric conductivity and optical transparency using rapid thermal annealing machine (RTP-CT100M) at 300 °C for 5 min in N_2 atmospheric pressure. After that, an acrylic layer was used as the support and protection layer, which was glued to the ITO electrode.

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A PDMS (184 Silicone Elastomer, Dow corning Co. Ltd.) solution (at a ratio of 10:1 for the base to the crosslinker by mass) was spun on the ITO/glass (1 mm) substrate at 1100 rpm for 10 seconds to obtain a PDMS layer with a fixed thickness of ~100 μm for all the devices. The PDMS layer was cross-linked on a hotplate at 95 °C for 25 min. Figure 1(b) are the photos for the completed glass plate and PDMS structures, showing the good transparency of both the structures. For electrical characterization of this work, a conductive aluminum (Al) tape was attached between the acrylic and ITO layer in the glass structure to lead out the copper wire for testing, and for the PDMS structure, the Al tape with a copper wire was pasted between the PDMS and ITO layer.

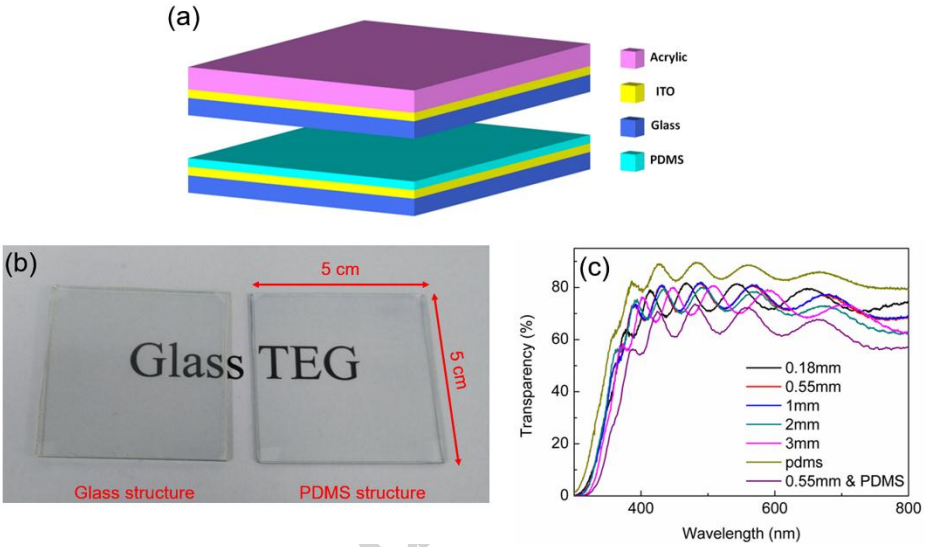

Figure 1 A 3D illustration of the TEG using glass and PDMS as the positively and negatively charged materials (a); the glass and PDMS structures (5×5 cm^2) on a written paper, showing good optical transmittance (b) and the transparency spectra of the PDMS structure, glass structure (five different thicknesses) and the whole device with 0.55mm glass (c).

A spectrophotometer (Hitachi Model U-4100) was used to characterize the optical transmittance of the PDMS and glass structures quantitatively. As shown in Figure 1(c), the transparency of the glass structure is ~81% in visible-light region, and is almost the same for the structures with different glass thicknesses. The PDMS structure has an optical transmittance of ~89%, better than that of the glass structures. The transparency of the integrated devices with the PDMS and glass layers is 73.6%, comparable to those reported transparent TEGs of various materials.[16, 19, 26]

The experimental setup for characterizing the contact-mode TEG performance is shown

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in Figure 2(a). A dynamic fatigue tester (Popwil Model YPS-1) was used to control the cyclic contact of the two plates of the TEGs. The tester is able to control the movement, force and frequency through programming. An oscilloscope (Tektronix MDO3022) and a picoammeter (Keysight B2981A) were used to measure the output voltage and current of the TEGs, respectively. As shown in Figure 2(b), the PDMS and glass parts of a TEG were attached to the upper fixed part and lower movable part of the fatigue tester, respectively, using an adhesive tape. The current and voltage of the TEG were acquired by connecting copper wires of the TEGs to the probes of the oscilloscope and picoammeter.

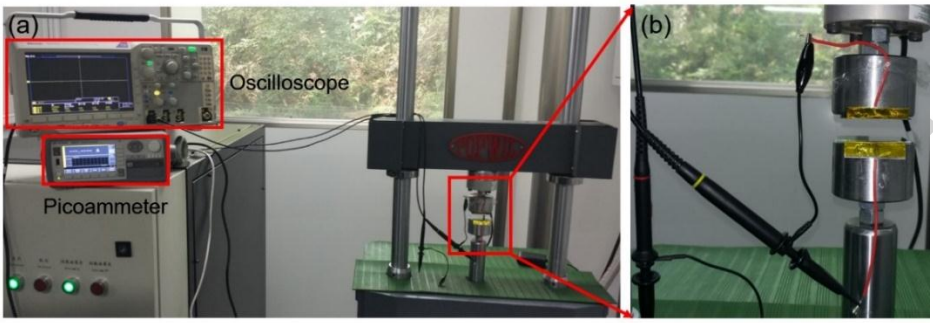

Figure 2 The experimental setup for the contact-mode glass TEG (a); and detailed setup of the TEG on the tester, the separated parts of TEG was attached to the movable stick, and the copper wires of the TEG were connected to the probe (b).

3. Results and discussion

The output performance of TEGs is highly dependent of the contact mode, distance, frequency and the force imposed, that affect how many electrons being electrostatically inducted and transferred. In all our tests, the glass part was moved vertically to make a contact with the PDMS plate. Figure 3(a) and 3(b) show the open circuit voltage V_{OC} and short circuit current I_{SC} of the TEG (1 mm glass) with contact force as a parameter. The distance between these two parts was fixed at 4 mm for all the tests and the contact frequency was 5 Hz. It is clear that the V_{OC} and I_{SC} increase gradually with contact force. The open voltage increases from 240 V to 540 V when the contact force rises from 10 N to 50 N. The I_{SC} at a contact force of 50 N reaches a peak of 20.9 μA, while it is only 6.3 μA when the contact force is 10 N. The increase of TEG output with the contact force is attributed to two factors. Firstly, the actual contact area of the two components increases under higher forces as the surfaces are not atomically flat, hence more electrons are electrostatically inducted. But the flat surface of

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the two materials used makes this effect relatively small. Secondly, the TEG is a capacitor with PDMS and glass dielectric layer sandwiched by two ITO electrodes once contacted. The capacitance of the TEG increases with increase in force as the PDMS becomes thinner due to its low mechanical strength. This leads to more charges (and charge density) being stored in the TEG, hence large output.[27]

The OC voltage and SC current of the same TEG with different contact frequencies at 50 N are shown in Figure 3(c) and 3(d). The V_{OC} and I_{SC} increase with the contact frequency before 5 Hz and tend to saturate at higher frequency. The OC voltage changes from 300 V at 1 Hz to 540 V at 5 Hz, and remains almost unchanged at 6 Hz contact frequency. Increase of the SC current and OC voltage of the TEG with contact frequency is attributed to fast induction and transferring of electrons under fast contacting, leading to high output.

The current, voltage, and power output under different load resistances are the most important parameters to characterize the performance of a TEG, and they are shown in Figure 3(e) and 3(f) for the TEG with 1 mm glass substrate. The dots are the experimental results and the lines are the fitted data, obtained under 50 N contact force and 5 Hz contact frequency. The voltage increases dramatically from 30 V to 372 V when the load increases from 1 MΩ to 200 MΩ, and then slowly increases to 428 V when the load is further increased to 1 GΩ. The tendency of the SC current change is opposite, and it decreases dramatically from 10.7 μA (1 MΩ) to 1.9 μA (300 MΩ), and then slowly to 0.5 μA when the load reaches 1 GΩ. The output power can be calculated by multiplying V_{OC} and I_{SC} with the same load, and the result is shown in Figure 3(f). The peak power is 1.54 mW occurred at around 40 MΩ of the load resistance.

The OC voltage and SC current of the TEG with 1 mm glass under different contact distances are shown in Figure 3(g) and 3(h). The contact force and frequency is 50 N and 2 Hz, respectively. The OC voltage gradually goes up from 248 V to 416 V when the contact distance increases from 2 mm to 6 mm. The SC current increases from 6.6 μA (2 mm) to 11 μA (6 mm). It can be seen clearly that the SC current shows the same trend with the OC voltage, which increases with the distance before 6 mm and saturates after that. The reason for the higher output under further distance before 6 mm distance is attributed to the higher velocity of the glass plate related to the PDMS structure. Higher speed of the moving part

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would result in higher charge transferring speed, and current function is time dependent, which means a larger current and voltage ($V = IR$). The relatively large fluctuation in output current under short-circuit and high contact frequency condition is a common phenomena for TEGs.[28] This is not instability as overall outputs remain almost same over periodical measurement. The reason for this is not clear, and we believe the uneven outputs are possibly caused by minor and random variation of surface roughness under forces as the microstructure deformation is not exactly the same from one place to another, leading to variation in outputs. These are under investigation.

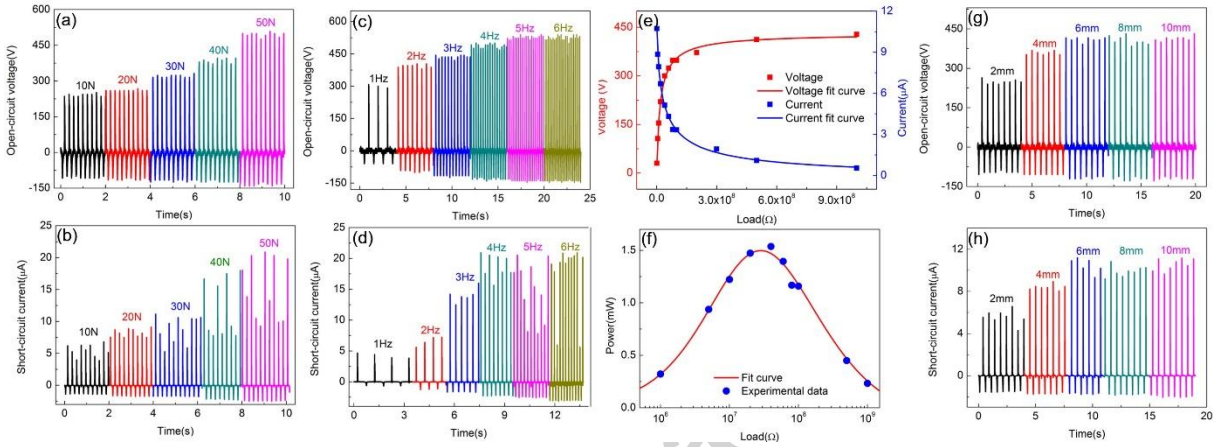

Figure 3 OC voltage (a) and SC current (b) under different contact forces, showing an increase trend. OC voltage (c) and SC current (d) under different contact frequencies, increasing with the frequency before 4 Hz and kept stable after 4 Hz frequency. The current and voltage (e) and power output (f) of the TEG under different loads. The peak power is 1.54 mW occurred at 40 MΩ. OC voltage (g) and SC current (h) under different contact distances, increasing with the distance before 6 mm and saturates after 6 mm distance.

The thickness of the glass substrate would affect the electric performance of the TEGs enormously. We measured the output of the TEGs with different glass thicknesses with the results summarized in Figure 4(a)-(c). The test conditions were 50 N contact force, 5 Hz contact frequency, and 4 mm distance between the glass and PDMS structures. Since the 0.18 mm glass was purchased from the different maker, its composite and material properties may be different from those with thickness from 0.55 mm to 3 mm. We only compare the performance of the TEGs with the glass thickness varies from 0.55 mm to 3 mm from the same maker.

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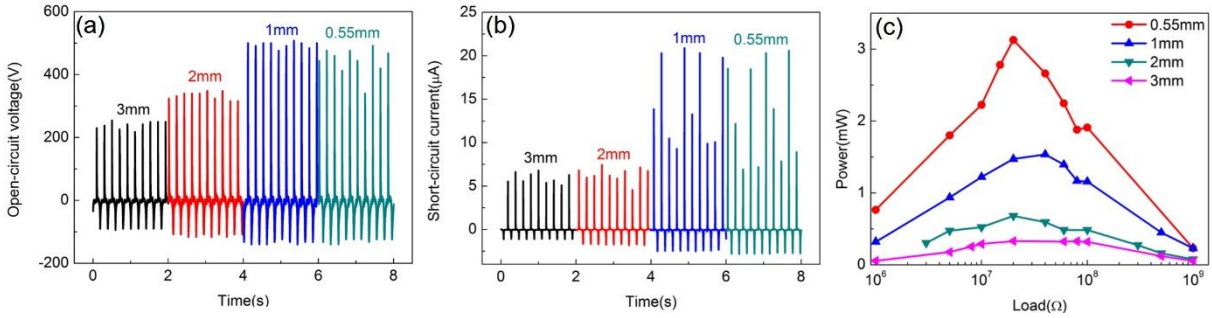

Figure 4 OC voltage (a), SC current (b) and power (c) of the TEGs with four different glass thicknesses (0.55 mm, 1 mm, 2 mm and 3 mm). The power output increases with decrease in glass thickness.

Generally, the OC voltage increases rapidly from ~250 V to ~500 V when the glass thickness decreases from 3 mm to 0.55 mm. The thinner one has a higher OC voltage. The SC current of the TEGs with 3 mm and 2 mm glasses are 6.8 μA and 7.4 μA, with minor increase as the glass becomes thinner. When the thickness of glass decreases to 1 and 0.55 mm, the maximum SC current dramatically increases to over 20 μA though it varies randomly. The maximum output power of the TEGs with different glass thicknesses were calculated and is shown in Figure 4(c). The TEG peak power is 0.33, 0.68, 1.54 and 3.13 mW for the device with the glass thickness of 3, 2, 1 and 0.55 mm, respectively. It is clear that the output power increases with the decrease of the glass thickness. It can be explained that for a thick glass, more charges would attenuate along the way from the glass surface to the ITO electrode, leading to decreased output power. The charge density can be calculated by integrating a single SC current pulse over time, and the inducted charge density of TEGs with different glass thicknesses is 17.1, 15.4, 8.84 and 6.28 μC/m^2 for the TEG with 0.55, 1, 2 and 3 mm glass thickness, respectively.

Theoretical analysis was conducted to investigate the performance of the TEG and compare with the experimental results. The V-Q-x model developed by Niu et al was used for analysis.[29] A first-order ordinary differential equation was used to describe the transferred charges (Q), current (I) and voltage (V) over time,

$$R\frac{\mathrm{d}Q}{\mathrm{d}t} = -\frac{Q}{S\varepsilon_0}\left(d_0 + x(t)\right) + \frac{\sigma x(t)}{\varepsilon_0} \qquad (1)$$

where R, t, ε_0, $x(t)$ and S represent the external load resistance, time, vacuum permittivity, distance between the two plates and contact area, respectively. d_0 is the effective thickness constant of a TEG, which is defined as,

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$$d_0 = \frac{d_1}{\varepsilon_{r1}} + \frac{d_2}{\varepsilon_{r2}} \quad (2)$$

where d_1 and d_2 are the thickness, ε_{r1} and ε_{r2} the relative permittivity of the upper and lower triboelectric material layers, respectively. The Q from Equation (1) can be solved by setting the boundary condition as follows,

$$Q(t_{initial}) = Q_{initial} \quad (3)$$

Initially, both $t_{initial}$ and $Q_{initial}$ are equal to zero. Once the plate starts to move, the current I is generated, which can be calculated by $\frac{\mathrm{d}Q}{\mathrm{d}t}$. The output voltage V can be calculated using the formula $V = IR$.

It was found that the type of plate movement could have a strong effect on the performance of the TEG and the accuracy of the model. In normal case, the trace of a plate motion is recognized as a cosine mode. However, the trace of the practical displacement of the TEG induced by the tester (for most commercial testers) is not exactly in cosine mode as shown in Figure 5(a). The rectangle dots are the practical movement data and the green line is the curve of cosine mode movement. To analyze the results accurately, the practical movement data must be used for analysis. The practical curve can be fitted using four sections as shown in Table I. Three straight lines and one sine curve were used for fitting and have achieved a good fitting with the coefficient of determination (R^2) over 0.99. The current, voltage and power for cosine and practical movement were calculated with the parameters listed in Table II. The parameters in the first four rows were utilized in both cosine and practical movement. The separation distance x_{max} and average velocity v were used to calculate the cosine movement:

$$x = x_{max}\left[\frac{1}{2} - \frac{1}{2}\cos\left(\frac{\pi v}{x_{max}}t\right)\right] \quad (4)$$

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Table I. Fitted curve formulas for practical movement.

Time t (s)	Movement formula x (mm)	R^2
[0, 0.022)	$x = 0$	1
[0.022, 0.025)	$x = 6.67037\mathrm{t} - 0.1467$	0.99589
[0.025, 0.064)	$\mathrm{y} = 61.34173\mathrm{t} - 1.51307$	0.99981
[0.064, 0.01]	$\mathrm{y} = 0.75497 + 2.41793\sin(\pi\frac{t + 0.68721}{0.12039})$	0.99899

Table II Parameters used for theoretical calculation of the TEGs in cosine and practical movement.

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Glass	d_1 = 1 mm, ε_{r1} = 7.2
PDMS	d_2 = 100 μm, ε_{r2} = 2.7
Contact area S	25 cm^2
Surface charge density σ	22 μC/m^2
Separation distance x_{max}	0.004 m
Average velocity v	0.04 m/s

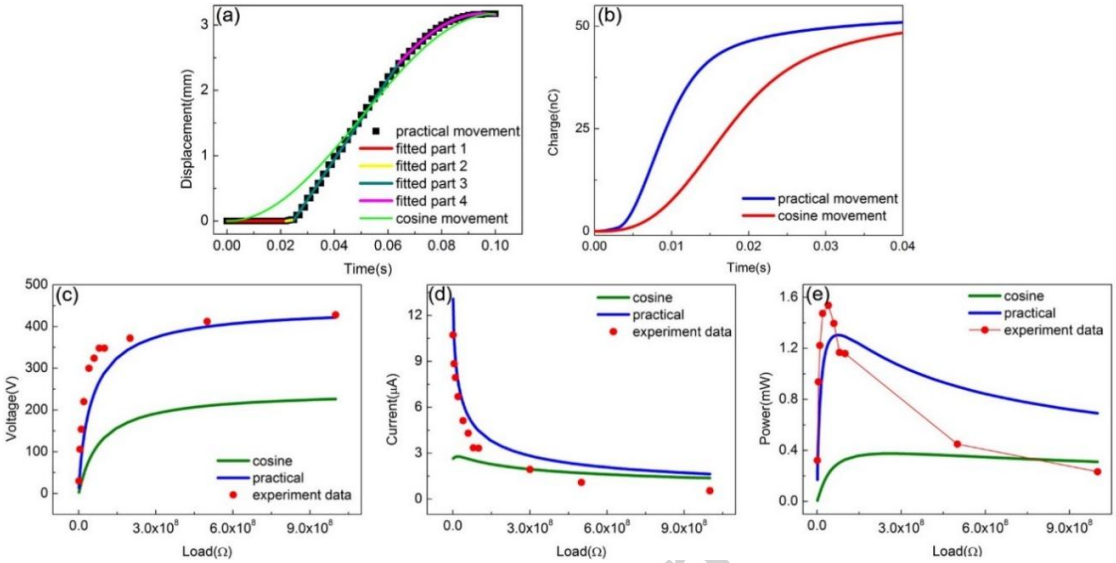

Figure 5 The cosine movement (green line) and the practical movement (black dot) showed great difference (a), and four curves were used to extract the formulas of the practical movement. (b) The calculated transferred charge over time with practical and cosine movement under a load of 77.5 MΩ. The calculated (c) voltage, (d) current and (e) power under cosine and practical movement were compared with the experiment data. The theoretical calculation using practical movement matched better with experiment data.

Figure 5(b) is the calculated charges transferred over time with practical and cosine movements under a load of 77.5 MΩ. Although the overall amount of transferred charges is same for both the movements at one cycle, which could be calculated as $S\sigma$, the speed of charge transferring $\frac{dQ}{dt}$, in practical movement is much faster than that in a cosine movement. This would generate much higher current as $I=\frac{dQ}{dt}$, voltage and power. Figure 5(c), 5(d) and 5(e) are the comparison of the calculated maximum voltage, current and power under different movements with the experimental data. The theoretical calculated results using cosine movement do not fit with the experiment data at all, and are several times smaller than the experimental results. On the other hand, using the practical motion trace, the calculated

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current and voltage are in good agreement with the experimental results, though there exist some discrepancy for the output power between the calculated and experimental results. The measured peak output power is 1.54 mW at 40 MΩ, while that is 1.3 mW at 77.5 MΩ in practical movement based calculation, whereas that calculated by cosine motion is well away from the experimental result. The results show that the TEG movement style needs to be considered for the model, and when the two parts of TEG are very close, higher relative speed of these two TEG parts is needed for a better TEG electric performance.

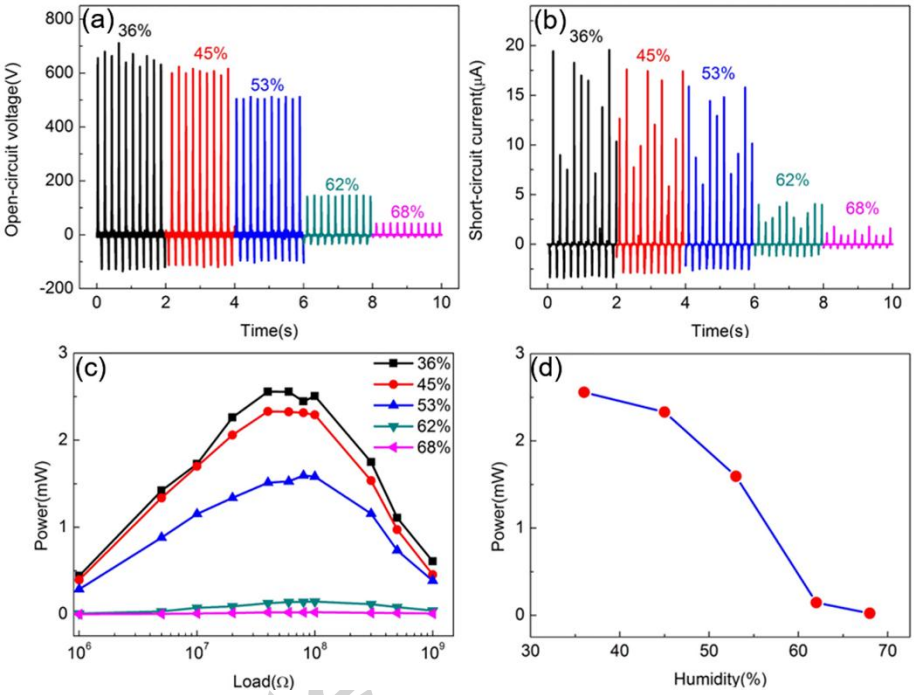

Figure 6 (a) OC voltage, (b) SC current, (c) power and (d) power peak of 0.18 mm glass TEG under different humidity. The electric performance deteriorated with higher humidity.

Humidity affects the TEG performance significantly.[30, 31] We also measured the electric performance of the glass TEGs under different humidity. The TEG with 0.18 mm glass was chosen as an example for this experiment. The distance between PDMS and glass plates, contact force and frequency was 4 mm, 50 N, 5 Hz, respectively. As shown in Figure 6(a) and 6(b), the SC current and OC voltage are 19.6 μA and 712 V under 36% relative humidity, and decrease to 1.8 μA and 41.6 V when the relative humidity is 68%. Figure 6(c) and 6(d) show the power of the TEG versus load under various humidity and dependence of the peak power on humidity. It is clear that the peak power saturates at about 2.6 mW for this device when the humidity is 36%RH or lower, and becomes almost zero when the humidity is

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65%RH or higher. For a material used in the TEGs, surface charge density is almost constant, the maximum power which can be generated by the TEG would be fixed, therefore further reduction of humidity would not increase the peak power. On the other hand, the surface conductivity of the material surface increases dramatically when humidity increases to a certain level[30], which will lead to the leakage of charges generated by triboelectric induction, no power is generated. The change of power conversion is drastic in the range between 45-60%. The results indicate it is better to avoid using TEGs in high humidity condition. By the way, it can also be seen from Figure 6(c) that although Figure 4(c) shows that the electric performance of TEG improves with thinner glass thickness, the electric performance of TEG with thinner 0.18 mm glass is found to be worse than those with thicker 0.55 mm glass and not follow the increase trend with decrease in glass thickness as shown in Figure 4(c), clearly implying that glass with different material properties would affect the performance of the TEGs. This also indicates glass based TEGs could be improved by alter the properties to obtain a higher power generation.

TEGs are normally designed to harvest mechanical energy, i.e. the TEGs will be subjected to rigorous mechanical impact or vibration, therefore mechanical reliability and stability of the TEG devices are extremely important for application. The performance of the TEGs was measured under cyclical contacts to investigate their reliability and stability. Figure 7 shows an example of the output of the TEG with 0.18 mm glass substrate up to 10,000 times, which is the recording capacity limit of the oscilloscope used. It is clear that the initial OC voltage is ~850 V, and declines gradually to ~700 V for the initial 2000 cyclic contacts. Then the OC voltage remains unchanged up to 10000 cyclic contacts. The initial decrease of the OC voltage is attributed to the decrease of the contact force of the PDMS and glass, which results from a thinner PDMS layer after 2000 times of compression. We have tested all devices, all showed similar behavior as in Figure 7, indicating that the glass-based TEGs have excellent stability and reliability.

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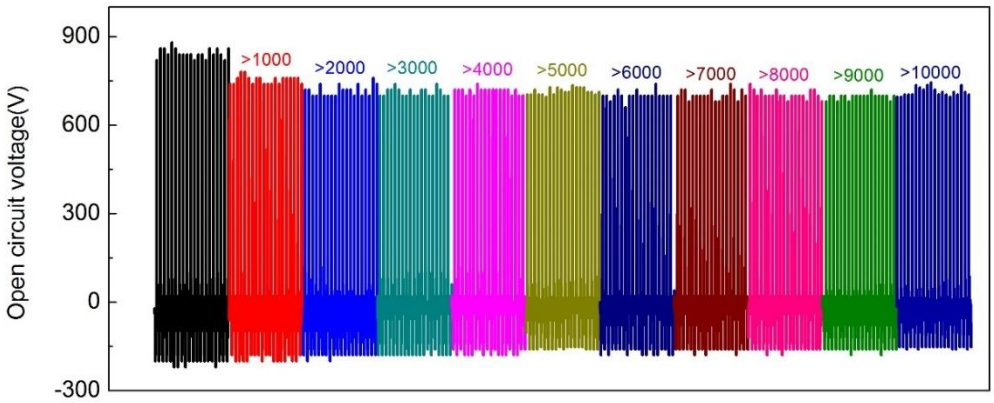

Figure 7 OC voltage of glass TEG after 10000 times of cyclic contacts, showing only a slight decrease at the beginning and good mechanical reliability.

It should be pointed out that this is a very preliminary work, using the commercially available flat surface glasses and PDMS layers, without any surface treatment and nanostructures, for feasibility study only. The charge and power densities obtained are very lower for the TEGs compared with others, and much work needs to be done to improve the efficiency of the transparent TEGs. On the other hand, a lot of techniques have been developed to enhance the power output and energy conversion efficiency. The most common effective methods include 1). Fabricate nanostructured surfaces for the two parts of the TEGs to increase the effective surface areas of the TEGs;[32, 33] 2). Use materials with high electron affinity or alter the material properties to achieve this; 3). Increase surface charge density either using polarized materials or injecting charges into the surface of the insulators.[34, 35] TEGs with a peak power over 300 W/m^2 have been achieved using the combined techniques discussed above.[20, 21] We expect that the power output of glass based TEGs would increases dramatically by using these methods for the glass and PDMS layers, particularly the ion injection method, thus it is possible to turn the abundant glass windows in modern society into useful energy conversion devices and systems to harvest waste mechanical energy such as wind, rains, vibration, shocks and impacts etc, which could contribute a great deal to the sustainable development.

4. Conclusion

In summary, transparent TEGs based on glass and PDMS structures have been fabricated and characterized. The transparency of glass and PDMS structures is over 81% and 89%, respectively. The glass based TEGs showed better energy harvesting performance (voltage,

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current and power) under higher contact force and frequency. The electric performance of the TEGs improved significantly with the use of thinner glass and operating at humidity lower than 45%RH. The TEG using 0.55 mm glass showed a performance with an OC voltage of 500 V, a SC current of 20.6 μA and peak power of 3.13 mW. The TEGs also showed stable performance after 10000 times cyclic contact tests. The work has shown that glass based TEGs have good performance with excellent stability and reliability, and has demonstrated the feasibility to turn the abundant glass windows into devices and systems for energy harvesting.

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Highlights

- Transparent TEGs based on commercial glasses have been developed.
- The outputs of the TEGs increase with contact force, frequency and distance, and with decreasing glass thickness.
- An improved model has been proposed for the TEG with excellent agreement with experiments.
- The TEGs have excellent stability without deterioration after tens of thousands contacts.